DOCUMENT RESUME

ED 060 617 EM 009 623

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TITLE	A Computer Simulation for the Study of Waves.
INSTITUTION	California Univ., Irvine. Physics Computer Development Project.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	15 Feb 72
NOTE	9p.
EDRS PRICE	MF-$0.65 HC-$3.29
DESCRIPTORS	*Computer Assisted Instruction; Instructional Innovation; *Physics Instruction; Programed Instruction; *Programed Materials

ABSTRACT

A computer program, designed for use in the second quarter of the beginning course for science and engineering majors at the University of California, Irvine, simulates an experimental investigation of a pulse in a rope. A full trial run is given, in which the student's problem is to discover enough about the disturbance of the rope to answer numerical questions about its behavior. Auxiliary facilities such as plotting and listing are provided. Checks are made as to the reasonableness of the student's strategy. It is hoped that through simulation, mathematical complexities in the physics material or deficiencies in the student's abilities can be bypassed. (RB)

A COMPUTER SIMULATION FOR THE STUDY OF WAVES

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February 15, 1972

Abstract

The computer program described, designed for use in the second quarter of the beginning course for science and engineering majors at the University of California, Irvine, simulates an experimental investigation of a pulse in a rope. The student is provided with a "measurement" facility; if he enters time and position he is told the rope displacement. His problem is to discover enough about the disturbance to answer numerical questions about its behavior. Auxiliary facilities such as plotting and listing are provided. Checks are made as to the reasonableness of the student strategy, and suggestions are given based on these checks. It is hoped that through this simulation students can in many cases "discover" the preservation of "shape," the $x - vt$ dependence of the pulse.

Newly developed beginning physics courses[1,2,3] often make strong demands on the students' mathematical ability. Thus the Feynman course or the Berkeley Physics course use mathematical techniques that previously had been confined to junior/senior level physics courses. Hence, a major problem associated with the teaching of newly developed high-level beginning courses is that of overcoming the mathematical barriers in the students' background. Students do not come into the physics course with noticeably better mathematical backgrounds so the burden of dealing with this new mathematical complexity falls on the physics instructor.

One feature of new courses is a more sophisticated approach to waves which assumes that even a freshman student can see the wave equation and explore some of its simple consequences. The wave equation (and the associated mathematics necessary for the student to understand what the equation means and how to generate solutions) is typical of the mathematical problems of the newer courses. Students are likely to be unfamiliar with both the notion of partial derivative and the idea of differential equations, either ordinary or partial. They are not able to solve such equations, so even if the teacher has a rational way of arriving at the equation, the solution must be developed within the physics class.

The computer can often be useful in a physics course in overcoming mathematical handicaps. For example, computational use of the computer allows the beginning course to get directly to the equations of motion as differential equations, rather than following the usual algebraic treatment.[4,5,6,7] Hence, it seems reasonable to ask if effective ways of using the computer to overcome the difficulties associated with the wave equation can be found. We might use computational approaches, but the important aim, to have students understand that the wave equation has solutions which depend on $x - vt$ or $x + vt$, characteristic of waves, is difficult to satisfy with direct numerical work. These solutions can be produced "out of the blue," but we hope to lead students to expect such solutions, offering a sounder basis for introducing these travelling patterns to the class.

e simulation described attempts to have students discover, through interaction with the computer, the x - vt dependence of a wave in a rope. It does not explicitly use this terminology; success is measured by a performance criterion. Students must use this relation or something equivalent to calculate values of the disturbance. Hence it would be followed by another program, lecture or text material showing that the x - vt disturbance is indeed a solution of the wave equation. In the Physics 5A-5B sequence at Irvine the students have seen the wave equation just before seeing this dialog.

This dialog might also be used in a phenomonologically oriented course which does not introduce the wave equation at this level, but where it is deemed important to have students learn about the x - vt dependence.

A Trial Run

To give the flavor of what it is like for a student to go through the program we examine a sample of a complete (but abbreviated) student use of the simulation dialog. It should be realized that the situation would be different for different students, and that any one trip through the program misses many aspects of the dialog. Thus the "help" messages are tailored to the requests for measurement the student has been putting in up to that point. Talking our way through an example should give a useful view of what is happening.

We assume that the student has signed on the computer, and knows that the name of the dialog is ROPEGAME. The dialog is requested by typing "ROPEGAME.PHYSICS."

First the computer introduces the problem:

```
THE PHYSICAL SYSTEM WE WILL EXPLORE IS
AN EXTREMELY LONG ROPE WITH A DISTURBANCE
IN IT IF YOU TELL ME A POSITION ALONG THE ROPE
AND A TIME, I WILL GIVE YOU THE DISTURBANCE,
THE DISPLACEMENT FROM EQUILIBRIUM. YOUR JOB
IS TO LEARN WHAT IS HAPPENING IN THE ROPE.

I WILL EVENTUALLY TURN THE TABLES, GIVING YOU
INFORMATION AND ASKING YOU TO PREDICT VALUES.

POSITION IS IN METERS AND TIME IN SECONDS;
DON'T ENTER UNITS.
```

The student is then expected to enter values for the position along the rope and the time; the computer calculates the disturbance at that point and displays the result. The student starts with no initial information about the disturbance, but has measurement-like facility for gathering information. In this example, the student tries more or less random values of position and time and does not find the disturbance; at any one time it is almost zero for most of the rope. Here are the initial measurements.

```
TIME = 5         POSITION = 5       DISTURBANCE =   0
TIME = 10        POSITION = 10      DISTURBANCE =   0
TIME = 45        POSITION = 869     DISTURBANCE =   0
TIME = 1.8E17    POSITION = 6.4     DISTURBANCE =   0
TIME = 100       POSITION = 200     DISTURBANCE =   0
```

Many students will find a disturbance in these first few measurements, because if the student makes the most likely choice, x = 0 and t = 0, a non-zero disturbance is encountered. But we don't want any student to miss the action forever, so if only zero disturbances in the rope occur in the first five measurements, the program offers guidance as to where to look for non-zero values.

```
JUST TO CONVINCE YOU THAT THE DISPLACEMENT
IS NOT ALWAYS ZERO, HERE ARE SOME POSITION
AND TIMES AT WHICH THE DISPLACEMENT IS
DISTINCTLY NON-ZERO.

TIME=    -2.24    POSITION= -8.24    DISPLACEMENT=  4.66E-2
TIME=    -0.06    POSITION=  0.34    DISPLACEMENT=  0.06
TIME=    -1.64    POSITION= -6.38    DISPLACEMENT=  0.28
TIME=    -0.66    POSITION= -2.63    DISPLACEMENT=  0.32
```

pattern of the disturbance is partially the result of random choices; each student receives a slightly different disturbance. However, the form of the disturbance has been chosen to make the dialog as profitable as possible and so stays the same for all students. We choose the same wave-velocity for all students.

Our hypothetical student now continues to make more measurements.

```
GRAPHS OR SKETCHES MIGHT BE USEFUL.
TIME = 0          POSITION = 0          DISTURBANCE =   0.22
TIME = 0          POSITION = 1          DISTURBANCE =   0.07
TIME = 0          POSITION = 2          DISTURBANCE =   0
TIME = 0          POSITION = -1         DISTURBANCE =   0
TIME = 0          POSITION = .5         DISTURBANCE =   0.10

THIS PUZZLE HAS A 'PAYOFF'. IF YOU
CAN DETERMINE HOW THIS DISTURBANCE BEHAVES,
YOU WILL UNDERSTAND AN IMPORTANT PRINCIPLE
INVOLVED IN MANY PHYSICAL SYSTEMS.
AFTER A FEW MORE MEASUREMENTS YOU CAN
TURN-THE-TABLE AND TRY TO PREDICT THE
BEHAVIOR OF THE ROPE.
TIME = 0          POSITION = -.5        DISTURBANCE =   0.09
TIME = 0          POSITION = 1.5        DISTURBANCE =   0.09
TIME = 0          POSITION = 1.1        DISTURBANCE =   0.09
TIME = 0          POSITION = 1.2        DISTURBANCE =   0.10
TIME = 0          POSITION = 1.3        DISTURBANCE =   0.11
```

After each group of five measurements additional advice is given. The student is confronted with the problem of dealing with a situation with two independent variables. The complexity of the situation is such that if a person picks unorganized values of these two variables, success or understanding is unlikely. We expect that some students, but not all, will develop in these early measurements what we consider to be a reasonable strategy. At this point the student is still in the dark as to the full details of what we expect. He or she has been told to study the disturbance in order to understand what is happening in the rope but does not know what kind of information about the rope we are going to request. So our student may not develop what we think of as a reasonable strategy.

We define reasonable strategy as meaning one of two things. Either measurements cluster around certain times, the snapshot point of view of looking at the detailed behavior of the rope at a number of different places, or measurements clustered around one or a few values of position, the point of view of standing at a fixed position and watching what happens as the disturbance in the rope passes.

This particular student has decided to find out what is happening in the rope at time t = 0, following the snapshot strategy.

After the student has made fifteen measurements we offer a new set of facilities.

```
YOU MAY HAVE SOME IDEA OF HOW THE ROPE IS
BEHAVING. AT THIS POINT I WILL CHANGE THE
RULES OF THE GAME. FOR:
     MEASUREMENT  TYPE M
     TURN-THE-TABLES TYPE T
     LIST OF MEASUREMENTS  TYPE L
     GRAPH     TYPE G
DON'T BE DISTURBED IF YOU CAN'T TURN THE
TABLES AT FIRST--I WILL GIVE YOU OTHER CHANCES,
```

I can see that our student can list values, useful particularly on a CRT terminal with no hard copy, and can receive a graph of the data.

Furthermore, for the first time the student can determine what it is that we are going to ask him to do in the program, the measure of success, by asking him to "turn-the-tables," and trying to predict values. We expect many students to try this at the earliest possible moment, and to do it often. There is no "penalty" for failure, and turn-the-tables can be tried many times. We will soon see an example of what is required.

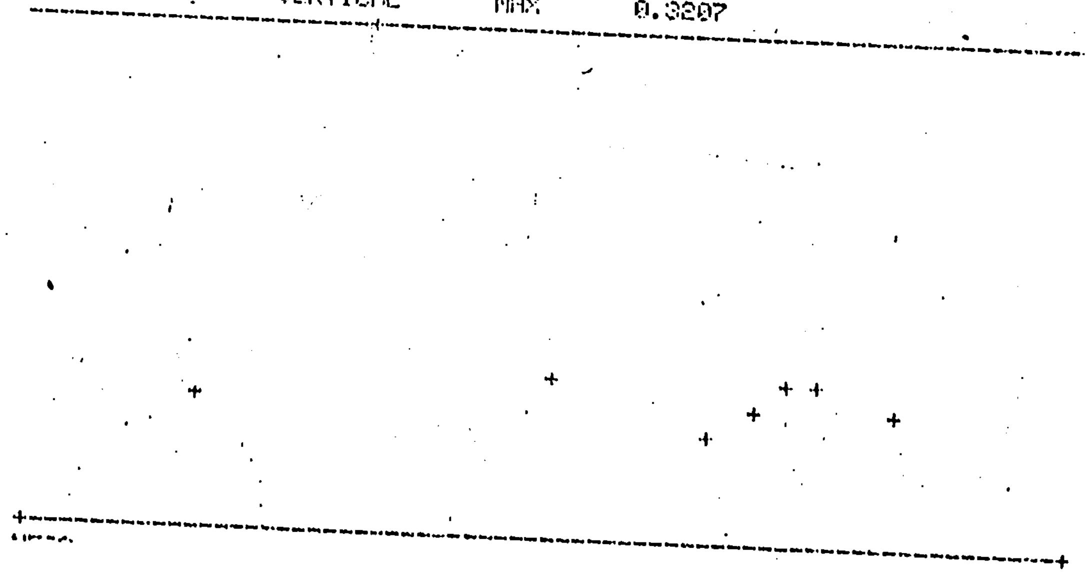
Our student first asks for a list.

```
MEASURE? LIST? TURN? GRAPH?   L
```

TIME	POSITION	DISTURBANCE
5	5	0
10	10	0
45	269	0
1.80E17	6.40	0
100	200	0
-2.24	-8.24	4.66E-2
-0.06	0.34	0.06
-1.64	-6.38	0.28
-0.66	-2.63	0.32
0	0.	0.32
0	1	0.07
0	2	0
0	-1	0
0	0.5	0.10
0	-0.5	0.09
0	1.5	0.09
0	1.10	0.09
0	1.20	0.10
0	1.30	0.11

Trying everything, our prototype now investigates what graphic facilities are available.

```
MEASURE? LIST? TURN? GRAPH?   G

WHAT INDEPENDENT VARIABLE DO YOU WANT FOR
YOUR GRAPH?    TIME

FOR WHAT VALUE OF POSITION?  1

NOT ENOUGH MEASUREMENTS AT THAT VALUE TO
BOTHER PLOTTING.
MEASURE? LIST? TURN? GRAPH?   G

WHAT INDEPENDENT VARIABLE DO YOU WANT FOR
YOUR GRAPH?    POSITION

FOR WHAT VALUE OF TIME?  0
-1     MIN    HORIZONTAL     MAX    2
 0     MIN     VERTICAL      MAX    0.3207
```



Graphs are only provided when a reasonable amount of data is available.

Our student decides to make a few more measurements; filling in what appear to be gaps in the data as shown on the graph. We allow a block of measurements.

```
MEASURE? LIST? TURN? GRAPH?   M

HOW MANY MEASUREMENTS IN THIS BLOCK?  7

TIME = 0            POSITION = -.9        DISTURBANCE =   0
TIME = 0            POSITION = -.8        DISTURBANCE =   1.31E-2
TIME = 0            POSITION = -.7        DISTURBANCE =   2.77E-2
TIME = 0            POSITION = -.6        DISTURBANCE =   5.30E-2
TIME = 0            POSITION = -.4        DISTURBANCE =   0.14
TIME = 0            POSITION = -.3        DISTURBANCE =   0.20
TIME = 0            POSITION = -.2        DISTURBANCE =   0.26
MEASURE? LIST? TURN? GRAPH?   M

HOW MANY MEASUREMENTS IN THIS BLOCK?  7

TIME = 0            POSITION = -.1        DISTURBANCE =   0.31
TIME = 0            POSITION = .1         DISTURBANCE =   0.31
```

Note the second block of seven measurements is not yet completed; at this point we are prepared to offer assistance.

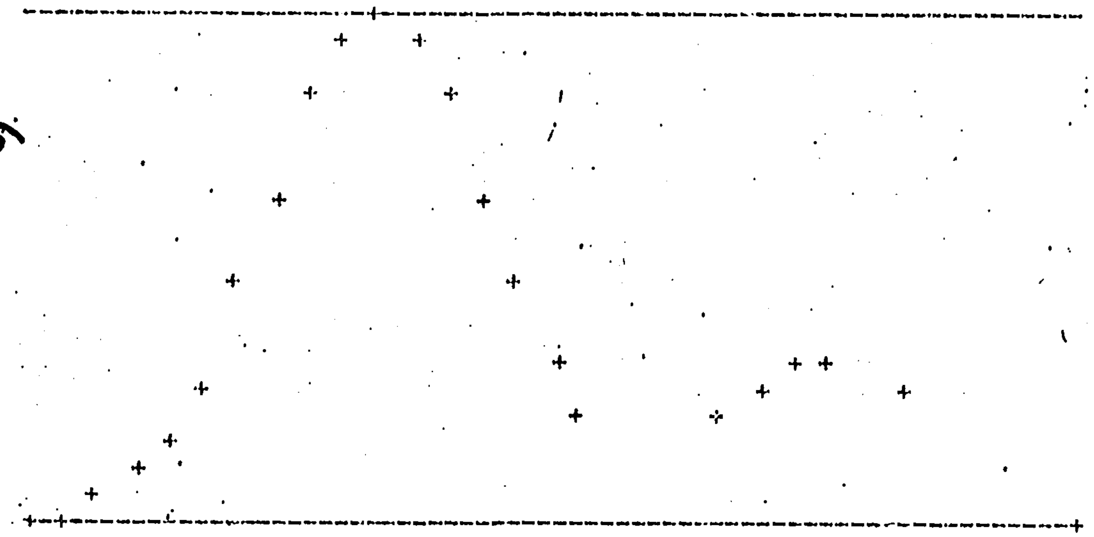
After the student has made more than 15 measurements, we periodically give advice and assistance. The advice depends on whether the student has developed a reasonable stragegy in the sense already suggested. If we cannot find a reasonable strategy, either the snapshot or the stand-at-one-point point of view, then we suggest a strategy by successively stronger hints. Finally we almost tell him how to proceed, because we don't want a student to sit forever taking random measurements.

After a reasonable strategy has been detected, a second set of hints is available, designed to suggest the moving pattern idea, the x - vt dependence that we hope will be the eventual conclusion.

In some of the hints we give additional values, showing what would happen with a consistent strategy. For example, in some cases we would plot a picture of the rope for t = 0, giving measurements not requested. Thus we show the disturbance at one time and hope that will be enough to get the student going.

typical student has been making meaningful measurements, so he gets a hint from the second set, and a suggestion that he "turn the tables." Then measurements continue, and he asks for a more complete graph.

```
BREAK AT LOC #SHOWLST+.16
;P

BREAK AT LOC #SAVETS+.25
;P

YOUR STRATEGY SEEMS REASONABLE. YOU SHOULD
HAVE SOME IDEA AS TO HOW THE ROPE IS BEHAVING.

YOU HAVEN'T TRIED TO BE ON THE OTHER END
YET, WHERE YOU TELL ME THINGS!
YOU SHOULD HAVE ENOUGH INFORMATION.
TIME = 0          POSITION = .2        DISTURBANCE =   0.26
TIME = 0          POSITION = .3        DISTURBANCE =   0.21
TIME = 0          POSITION = .4        DISTURBANCE =   0.15
TIME = 0          POSITION = .6        DISTURBANCE =   0.06
TIME = 1          POSITION = 1         DISTURBANCE =   0
MEASURE? LIST? TURN? GRAPH?   G

WHAT INDEPENDENT VARIABLE DO YOU WANT FOR
YOUR GRAPH?    POSITION

FOR WHAT VALUE OF TIME?  0
-1      MIN     HORIZONTAL      MAX       2
 0      MIN      VERTICAL       MAX       0.3207
```



The disturbance at t = 0 clearly has two humps. Each student using the dialog receives a disturbance of this type, but with parameters chosen randomly within limits.

The student next follows the suggestion to try turn the tables.

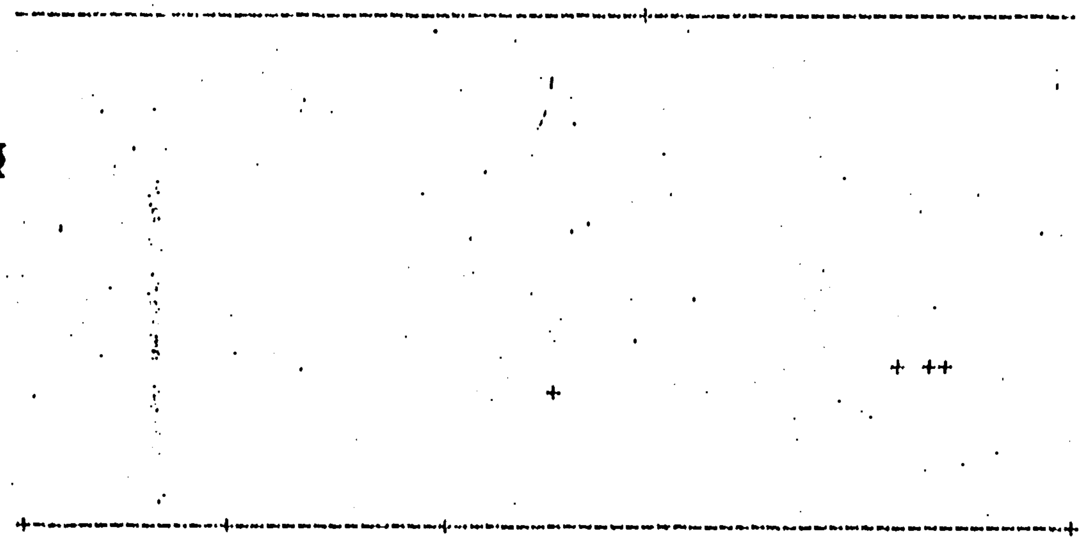
```
MEASURE? LIST? TURN? GRAPH?   T

YOU KNOW ALREADY THAT AT T = -1.64 AND AT  X = -6.38
     THE DISTURBANCE =    0.28

AT T =    4.20  THE DISPLACEMENT IS TO BE THE SAME.
WHAT VALUE OF POSITION MAKES THIS THE CASE?

?0

TRY ONCE MORE. ACCURACY .1.

?0

I CAN'T IDENTIFY YOUR RESPONSE AS CORRECT.
THE POSITION SHOULD BE    16.97
TRY MORE MEASUREMENTS. AND TYPE TURN WHEN
YOU THINK YOU CAN ANSWER QUESTIONS LIKE THIS.
```

This student doesn't have enough information to make the prediction, so he types only zeros. Note that the question works partially with data already obtained, and partially with randomly generated new data.

The student cannot yet make the calculation because his measurement has not been in enough detail to determine the velocity of the disturbance. You can see, although the student will not see it yet, that ability to answer the questions is based on an understanding that the displacement function giving this disturbance in the rope as a function of position and time always depends on position and time in the combination (x - vt). The student is given several tries.

Our hypothetical student, quicker than most, now goes after the velocity of the disturbance.

```
MEASURE? LIST? TURN? GRAPH?   M

HOW MANY MEASUREMENTS IN THIS BLOCK?  10

TIME = 1            POSITION = 2          DISTURBANCE =   0
TIME = 1            POSITION = 3          DISTURBANCE =   0
TIME = 1            POSITION = 4          DISTURBANCE =   0.32
TIME = 1.5          POSITION = 6          DISTURBANCE =   0.32
TIME = 2            POSITION = 8          DISTURBANCE =   0.32
ARE YOU MAKING GRAPHS OF THE ROPE
HAVE YOU THOUGHT ABOUT THE BEHAVIOR OF THE
STRING AT DIFFERENT TIMES. WHAT DOES IT LOOK
LIKE AT ANY ONE TIME? THEN WHAT HAPPENS TO IT?
I SEE THAT YOU ARE HOLDING THE
TIME CONSTANT IN MANY MEASUREMENTS
TIME = 1            POSITION = 5.2        DISTURBANCE =   0.10
TIME = 1            POSITION = 5.3
JUST A NUMBER, PLEASE.
TIME = 1            POSITION = 5.3        DISTURBANCE =   0.11
TIME = 1            POSITION = 5.4        DISTURBANCE =   0.10
TIME = 1            POSITION = 6          DISTURBANCE =   0
TIME = 1            POSITION = 3.5        DISTURBANCE =   0.09
MEASURE? LIST? TURN? GRAPH?   G

WHAT INDEPENDENT VARIABLE DO YOU WANT FOR
YOUR GRAPH?    POSITION

FOR WHAT VALUE OF TIME?  1
 1      MIN      HORIZONTAL      MAX      6
 0      MIN       VERTICAL       MAX      0.3207
```



Here the choice of pattern, a double Gaussian with unequal peaks, assists in identifying the form. In particular if the maximum is known, we can find how the maximum moves to determine the wave velocity. The graph suggests a moving pattern, keeping the same shape in time, and moving with a velocity of 4 meters/second.

So the student proceeds, with confidence, to turn the tables! Most students will not succeed this quickly, so this one must be bright.

```
MEASURE? LIST? TURN? GRAPH?   T

YOU KNOW ALREADY THAT AT T =  0 AND AT  X =  0
     THE DISTURBANCE =    0.32

AT T =    5.36  THE DISPLACEMENT IS TO BE THE SAME.
WHAT VALUE OF POSITION MAKES THIS THE CASE?

?21.5

SEEMS GOOD. LET'S TRY ANOTHER OF THE
SAME TYPE.
YOU KNOW ALREADY THAT AT T =  0 AND AT  X =  1.20
     THE DISTURBANCE =    0.10

AT T =    3.60  THE DISPLACEMENT IS TO BE THE SAME.
WHAT VALUE OF POSITION MAKES THIS THE CASE?

?14.4

TRY ONCE MORE. ACCURACY .1.

?15.6

FINE.... NOW WE'LL PLAY THE GAME A SLIGHTLY
DIFFERENT WAY.
```

```
HERE ARE TWO MEASUREMENTS FOR TIME T=   1
FOR X=  3.5     THE ROPE DISPLACEMENT IS  0.09

AND FOR X =  6     DISPLACEMENT IS  0

AT TIME T =  0.15  AND AT THE POSITION  X =  0.11
THE DISPLACEMENT IS THE SAME AS IN THE FIRST
MEASUREMENT ABOVE,  0.09
AT THE SAME TIME WHAT WILL BE THE VALUE OF
X THAT GIVES THE DISPLACEMENT THE SAME AS
THAT OF THE SECOND MEASUREMENT ABOVE?

?22.6

GIVE IT ANOTHER TRY...THINK ABOUT WHAT
HAPPENS WITH THE STRING IN TIME.

?2.6

AS FAR AS I CAN TELL WITH MY LIMITED ABILITY
YOU HAVE SUCCESSFULLY LEARNED HOW THE
ROPE IS BEHAVING. THE BEHAVIOR THAT WE HAVE
BEEN EXAMINING IS TYPICAL OF A WAVE, AN
IMPORTANT PHYSICAL CONCEPT.

PLEASE TYPE A VERBAL DESCRIPTION OF WHAT IS
HAPPENING WITH OUR ROPE. USE THE LINE FEED
FOR MULTIPLE LINES, ONLY USING CARRIAGE RETURN
WHEN FINISHED. IF YOU WISH TO HAVE YOUR
DESCRIPTION EVALUATED BY THE INSTRUCTOR TO
SEE IF YOU UNDERSTAND THIS ASPECT OF WAVE
BEHAVIOR, TYPE YOUR NAME ALSO.

ANY COMMENTS ABOUT THE PROGRAM  ARE ALSO WELCOME.

?A PATTER WITH TWO HUMPS IS MOVING DOWN THE STRING.
THE PATTER APPEARS TO STAY TO SAME SHAPE.  ITS VELOCITY
IS FOUR METERS PER SECOND.

CONGRATULATIONS AND GOODBYE!
```


We ask the successful student to comment on the dialog, which might help us to improve it, and we congratulate him on his understand of what is happening in the rope.

We do not want a student to spend forever at this game; he or she may need other ways of learning the x - vt dependence. We have an arbitrary cutoff of 100 measurements. If the student has not succeeded by then, we check to see if "turn the tables" has been used. If not we insist. But if it has we ask for comments, express our sorrow that we have not succeeded in accomplishing our objective, and suggest talking with the teacher. In common with all dialogs the comments are stored in a file for future evaluation.

Conclusions

ROPEGAME was used by about forty students in the beginning course for science and engineering majors at Irvine during 1971. It was also used by about a dozen upper division physics students. In its use with the beginning students, less than half completed the program. About half the students liked the program, and half did not; in contrast to other dialogs, few students were neutral.

Thus it is clear that, particularly for the weaker students, the program does not sustain interest long enough for them to make the "discovery." The game-like aspects of the program are not sufficiently pronounced, in spite of our calling it a game, to motivate all students to complete the comparatively difficult task. On the other hand, the students who did complete the program were enthusiastic and excited about this method of learning about an important property of waves.

With the junior-senior students a different situation developed. All these students knew in advance the basic physics to be "discovered" in the program, yet most of them were enthusiastic users. Perhaps because they already knew the underlying results, they could consider it more of a game, and they tended to be more involved. A colleague, watching advanced students at work,

speculated that the program might be useful for selecting students who will be successful in experimental research, even at an early level, because the persistence needed to tackle tough problems would show up. This seems a reasonable conjecture.

The difficulties experienced with ROPEGAME are similar to those experienced with other dialogs used in the Physics Computer Development Project. It turns out to be particularly difficult to write simulations which accomplish an educational task. Simulations can certainly be exciting. This particular program was exciting for some students, and such simulations as our lunar landing program have stimulated a much wider audience of students. However, whether students, at least most of them, learn, anything from simulations is another matter entirely. It seems to us that a learning environment is much more difficult to produce than a stimulating environment.

One minor detail is to be changed in the next version of ROPEGAME. We had taken the disturbance to be always positive. Many people expect the disturbance to be both positive and negative, so we intend to make the smaller Gaussian hump negative.

Following our recent work with students[8] we will probably produce a version particularly oriented to graphic terminals, allowing students to take "pictures". They will gain information much more quickly, perhaps even making the problem too trivial, or perhaps giving more information than is usable.

Comments and suggestions from readers would certainly be welcome.

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